MiniBooNE’s First Neutrino Oscillation Result

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Outline

1. Motivation and Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
5. First Results
6. Updates Since First Result
if neutrinos have mass...

a neutrino that is produced as a $\nu_\mu$

- (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)

might some time later be observed as a $\nu_e$

- (e.g. $\nu_e n \rightarrow e^- p$)
Neutrino Oscillation

\[
\begin{pmatrix}
\nu_\mu \\
\nu_e
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

- Consider only two types of neutrinos

- If weak states differ from mass states
  - i.e. \((\nu_\mu, \nu_e) \neq (\nu_1, \nu_2)\)

- Then weak states are mixtures of mass states

\[
|\nu_\mu(t)\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle
\]

\[
P_{osc}(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2
\]

- Probability to find \(\nu_e\) when you started with \(\nu_\mu\)
Neutrino Oscillation

- In units that experimentalists like:

\[ P_{\text{osc}}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (\text{eV}^2) L (\text{km})}{E_\nu (\text{GeV})} \right) \]

- Fundamental Parameters
  - mass squared differences
  - mixing angle

- Experimental Parameters
  - \( L \) = distance from source to detector
  - \( E \) = neutrino energy

![Graph of neutrino oscillation probability](attachment:image.png)
Oscillation Signals

- **Solar** - Homestake, ... SNO
  - confirmed by reactors

- **Atmospheric** - Super-K, ...
  - confirmed by accelerators

- **Accelerator** - measured by LSND
  - unconfirmed!
The Problem

- Three different neutrino oscillation signals
- Three independent $\Delta m^2$
- Problem: We only need two!
- Explanation requires physics well beyond the standard model
- Is it true?
Verifying LSND

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27\Delta m_{12}^2 \frac{L}{E}) \]

- LSND interpreted as 2 \( \nu \) oscillation
- Verification requires same \((L/E)\) and high statistics
- Different systematics
- MiniBooNE chose higher \( L \) and \( E \)
- **Strategy**: search for \( \nu_e \) excess in \( \nu_\mu \) beam
TODAY: MiniBooNE’s initial results on testing the LSND anomaly

1- Generic search for $\nu_e$ excess in $\nu_\mu$ beam

2- Analysis of data within 2 $\nu$ appearance only context
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Target & Horn

Main components of Booster Neutrino Beam (BNB)
(96M and 146M+ pulses)

MiniBooNE Overview

Booster

Magnetic focusing horn

Decay region

Absorber

450 m dirt

Detector

\[ \nu_e \rightarrow \nu_e \]

JL Raaf
Meson Production

- External meson production data
- HARP data (CERN)
- Parametrisation of cross-sections
- Sanford-Wang for pions
- Feynman scaling for kaons

MiniBooNE Overview
ν Flux

- 99.5% pure muon flavour
- 0.5% intrinsic $\nu_e$
- Constrain $\nu_e$ content with $\nu_\mu$ measurements

MiniBooNE Overview
MiniBooNE Overview

Detector
Neutrino Interactions

MiniBooNE is here

CC / NC quasi-elastic scattering (QE)
42% / 16%

CC / NC resonance production (1π)
25% / 7%
Mineral Oil Optics

- Production:
  - Cherenkov and scintillation
- Secondary:
  - Fluorescence and scattering (Raman, Rayleigh)

Extinction Rate for MiniBooNE Marcol 7 Mineral Oil
Track Images

- Muons
- full rings
- Electrons
- fuzzy rings
- Neutral pions
- double rings
PMT Hit Clusters

- PMT hits clusters in time form “subevents”
  - $\nu_\mu$ events have 2 subevents
    - $\mu$, followed by $e$
  - $\nu_e$ events have 1 subevent
- Simple cuts on subevents remove cosmic backgrounds
  - “pre-cuts”
Charged particles produce Cherenkov and scintillation light in oil.

PMTs collect photons, record $t$, $Q$.
Reconstruct tracks by fitting time and angular distributions.
Find position, direction, energy.
Detector Stability

Events per $1 \times 10^{15}$ POT vs Week

Number of minutes

- Observed
- Predicted

Number of neutrino candidates in minute
1. Motivation and Introduction

2. Description of the Experiment

3. Analysis Overview
   1. Signal and Backgrounds
   2. Strategy

4. Two Independent Oscillation Searches

5. First Results

6. Updates Since First Result
## Blind Analysis

Opened specific boxes with $<1\sigma \nu_e$ signal

<table>
<thead>
<tr>
<th>Initial Open Box</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>all non-beam-trigger data</td>
<td>calibration and MC tuning</td>
</tr>
<tr>
<td>0.25% random trigger</td>
<td>unbiased data studies</td>
</tr>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>measure flux, $E_{\nu,QE}$, oscillation fit</td>
</tr>
<tr>
<td>$\nu_\mu$ NCpi0</td>
<td>measure rate for MC tuning</td>
</tr>
<tr>
<td>$\nu_\mu$ CC1pi+</td>
<td>check rate for MC</td>
</tr>
<tr>
<td>$\nu_\mu$-e elastic</td>
<td>check MC rate</td>
</tr>
<tr>
<td>“dirt”</td>
<td>measure MC rate</td>
</tr>
<tr>
<td>all events with $E_\nu &gt; 1.4$ GeV</td>
<td>check MC rate</td>
</tr>
</tbody>
</table>

### Second Step

| One closed signal box             | explicitly sequester signal, 99% of data open |
---|---|---|
For robustness, MiniBooNE has performed two independent oscillation analyses.
Signal and Backgrounds

Stacked signal and backgrounds after $\nu_e$ event selection

Oscillation $\nu_e$
Example oscillation signal
$\Delta m^2 = 1.2 \text{ eV}^2$
$\sin^2 2\theta = 0.003$
Fit for excess as a function of reconstructed $\nu_e$ energy
Signal and Backgrounds

STACKED SIGNAL AND BACKGROUND AFTER $\nu_e$ EVENT SELECTION

$\nu_e$ FROM $K^+$ AND $K^0$

- Use fit to kaon production data for shape.
- Use high energy $\nu_e$ and $\nu_\mu$ in-situ data for normalisation cross-check.
Signal and Backgrounds

**ν_e from μ⁺**

\[ p + Be \rightarrow \pi^+ \rightarrow \nu_\mu, \mu^+, \nu_e, \nu_\mu \mathrm{e}^+ \]

Measured with in-situ ν_μ CCQE sample
- Same ancestor π⁺ kinematics
- Most important background
  - Constrained to a few %

Stacked signal and backgrounds after ν_e event selection

Reconstructed E_ν (MeV)
Signal and Backgrounds

MisID $\nu_\mu$

- $\sim 46\% \pi^0$
  - Determined by clean $\pi^0$ measurement

- $\sim 16\% \Delta \gamma$ decay
  - $\pi^0$ measurement constrains

- $\sim 14\%$ “dirt”
  - Measure rate to normalise and use MC for shape

- $\sim 24\%$ other
  - Use $\nu_\mu$ CCQE rate to normalise and MC for shape

stacked signal and backgrounds after $\nu_e$ event selection
Strategy

Incorporate in-situ data whenever possible

- MC tuning with calibration data
  - energy scale
  - PMT response
  - optical model

- MC tuning with neutrino data
  - cross section nuclear model parameters
  - \( \pi^0 \) rate constraint

- Constraining systematic errors with neutrino data
  - ratio method: \( \nu_e \) from \( \mu \) decay
  - combined fit to \( \nu_e \) and \( \nu_\mu \) data

Recurring theme: good data-MC agreement
MC Tuning

Good data/MC agreement

- Basic PMT hit distributions showing details of optical model
- Aggregate PMT hit distributions showing gross detector behaviour
MC Tuning

**Good data/MC agreement**

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Recurring theme: good data-MC agreement
\( \nu_\mu \) CCQE events

*Used to measure flux and check \( E_\nu^{QE} \) reconstruction*

\[
E_\nu^{QE} = \frac{1}{2 M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)} \cos \theta_\mu}
\]

- 2 subevents: e, \( \mu \)
- Require e be located near end of \( \mu \) track

- \( E_\nu^{QE} \) resolution ~10%
Tuning CCQE MC

$Q^2$ distribution fit to tune empirical parameters of nuclear model ($^{12}$C)

Data

$\chi^2$/ndf = 4.7 / 13

good data-MC agreement in variables not used in tuning!
\( \pi^0 \) Mis-ID Backgrounds

- \( \pi^0 \)s are reconstructed outside mass peak if:
  - asymmetric decays
  - fake 1-ring
  - 1 of 2 photons exits
  - high momentum \( \pi^0 \) decays produce overlapping rings
The MC $\pi^0$ rate ($\text{flux} \times \text{xsec}$) is re-weighted to match the measurement in $p_\pi$ bins.

good data-MC agreement in variables not used in tuning!
Incorporate in-situ data whenever possible

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  - energy scale
  - PMT response
  - optical model

- MC tuning with neutrino data
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Recurring theme: good data-MC agreement
Analysis Strategy 1: Ratio Method

- MC predicts a range of $\nu_\mu$ fluxes
- Use data/MC ratio of $\nu_\mu$ CCQE events to re-weight parent $\pi^+$

$\nu_e$ from $\mu$ decay

- unweighted
- re-weighted

$\nu_e$ from $\mu$ decay
Analysis Strategy 2: Combined Fit

- For each $E_\nu$ bin $i$,
  \[ \Delta_i = N_{i}^{DATA} - N_{i}^{MC} \]

- Raster-scan in $\Delta m^2$ and $\sin^2 2\theta_{\mu e}$ to calculate $\chi^2$ over $\nu_e$ and $\nu_\mu$ bins

\[
\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} \Delta_i M_{ij}^{-1} \Delta_j
\]

- Systematic error matrix includes uncertainties for $\nu_e$ and $\nu_\mu$
Error Matrix

\[ M_{ij} = \frac{1}{N_{\alpha}} \sum_{\alpha=1}^{N_{\alpha}} (N_i^{\alpha} - N_{i}^{MC})(N_j^{\alpha} - N_{j}^{MC}) \]

- Use MC variations to study systematic uncertainties
- Vary underlying parameters and compare to “central value” MC
- Total error matrix is sum of individual matrices

Example of $E_{\nu}^{QE}$ distributions for several MC variations
## Systematic Errors

<table>
<thead>
<tr>
<th>Neutrino flux predictions</th>
<th>constraint?</th>
</tr>
</thead>
<tbody>
<tr>
<td>meson production cross sections</td>
<td>✓</td>
</tr>
<tr>
<td>meson secondary interactions</td>
<td>✓</td>
</tr>
<tr>
<td>focussing horn current</td>
<td>✓</td>
</tr>
<tr>
<td>target and horn system alignment</td>
<td></td>
</tr>
<tr>
<td>Neutrino interaction cross sections</td>
<td></td>
</tr>
<tr>
<td>nuclear model</td>
<td>✓</td>
</tr>
<tr>
<td>rates and kinematics for relevant processes</td>
<td>✓</td>
</tr>
<tr>
<td>resonance width and branching fractions</td>
<td>✓</td>
</tr>
<tr>
<td>Detector modelling</td>
<td></td>
</tr>
<tr>
<td>optical model of light propagation</td>
<td>✓</td>
</tr>
<tr>
<td>PMT charge and time response</td>
<td>✓</td>
</tr>
<tr>
<td>electronics &amp; DAQ model</td>
<td>✓</td>
</tr>
<tr>
<td>neutrino interactions in dirt surrounding detector</td>
<td>✓</td>
</tr>
</tbody>
</table>
Outline

1. Motivation and Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
   1. Reconstruction and Event Selection
   2. Systematic Uncertainties
5. First Results
6. Updates Since First Result
2 Independent Searches

- Method 1: Track Based Analysis
  - Careful Reconstruction of particle tracks
  - Identify particle type by likelihood ratio
  - Use ratio method to constrain backgrounds
  - Strengths:
    - Relatively insensitive to optical model
    - Simple cuts on likelihood ratios

- Method 2: Boosted Decision Trees
  - Classify events using boosted decision trees
  - Cut on output variables to improve event separation
  - Use combined fit to constrain backgrounds
  - Strengths:
    - Combine weak variables to form strong classifier
    - Better constraints on backgrounds
Particle Identification

- Reconstruct under 3 hypotheses: $\mu$-like, e-like and $\pi^0$-like
- $\nu_e$ particle ID cuts on likelihood ratios
  - chosen to maximise $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity
e/µ Likelihood

- $\nu_\mu$ CCQE data (with muon decay electron) compared to $\nu_\mu$ data with no decay electrons ("All but signal")
- Removes most muon events
e/$\pi^0$ Likelihood

- “All but signal” (open) data and MC
- PID uses cuts on
  - likelihood ratio
  - reconstructed $\pi^0$ mass
- Opened sidebands before unblinding full data sample
Signal and background

• “Analysis region” defined to be 475-1250 MeV

• Signal efficiency higher at low energy

• Backgrounds higher there too...
Signal and background

- “Analysis region” defined to be 475-1250 MeV
- Signal efficiency higher at low energy
- Backgrounds higher there too...
Signal and background

**Predicted $\nu_e$ energy distribution**

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>475-1250 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e(\mu$ decay)</td>
<td>132</td>
</tr>
<tr>
<td>$\nu_e(K$ decay)</td>
<td>94</td>
</tr>
<tr>
<td>Radiative $\Delta$</td>
<td>20</td>
</tr>
<tr>
<td>NC$\pi^0$</td>
<td>62</td>
</tr>
<tr>
<td>Dirt</td>
<td>17</td>
</tr>
<tr>
<td>Other</td>
<td>33</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>358</strong></td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td><strong>163</strong></td>
</tr>
</tbody>
</table>
# Uncertainties

<table>
<thead>
<tr>
<th>source</th>
<th>uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux from $\pi^+ / \mu^+$ decay</td>
<td>6.2</td>
</tr>
<tr>
<td>Flux from $K^+$ decay</td>
<td>3.3</td>
</tr>
<tr>
<td>Flux from $K^0$ decay</td>
<td>1.5</td>
</tr>
<tr>
<td>Target and beam models</td>
<td>2.8</td>
</tr>
<tr>
<td>$\nu$-cross section</td>
<td>12.3</td>
</tr>
<tr>
<td>NC $\pi^0$ yield</td>
<td>1.8</td>
</tr>
<tr>
<td>External interactions</td>
<td>0.8</td>
</tr>
<tr>
<td>Optical model</td>
<td>6.1</td>
</tr>
<tr>
<td>Electronics &amp; DAQ model</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>constrained total</strong></td>
<td><strong>9.6</strong></td>
</tr>
</tbody>
</table>

Note: “total” is **not** the quadrature sum -- errors are further reduced by constraints from $\nu_\mu$ data.
• Sensitivity to oscillations

• “Primary” analysis chosen on the basis of this plot

• Chosen before opening the box!
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Opening “The Box”

After applying all analysis cuts

• **Step 1:** Fit sequestered data to oscillation hypothesis
  ✓ Don’t return fit parameters
  ✓ Apply unreported parameters to MC, check diagnostic variables
  ✓ Return $\chi^2$ for diagnostic variables

• **Step 2:** Open plots from Step 1
  • Plots chosen to be useful but not “revealing”

• **Step 3:** Report only the (unsigned) $\chi^2$ from fit
  • No fit parameters returned

• **Step 4:** Compare EnuQE for data and MC
  • Blindness broken

• **Step 5:** Present results within two weeks
Training for a blind search

On March 26, 2007 we opened the box...
Opened box!

- Counting Experiment (475-1250 MeV)
- Expect 358 ± 19(stat) ± 35(sys)
- Observe 380
- Significance 0.55 σ
Exclusion Curve

- No evidence for $\nu_\mu \rightarrow \nu_e$
  
- $2\nu$ appearance only oscillations

- Independent second analysis finds similar result

- Incompatible with LSND at 98% CL

- cf. KARMEN2 compatible at 64%

---

MiniBooNE First Result

- $\sin^2(2\theta)$ upper limit
- MiniBooNE 90% C.L.
- BDT analysis 90% C.L.
What Does It Mean?

• With the blind analysis, we have asked the question:

Do $\nu_\mu$s oscillate directly to $\nu_e$s with $\Delta m^2 \sim 1 \text{eV}^2$, ala LSND?

• We have a clear answer:

NO

More work yet to do...
At lower energy...

- Lowering the energy threshold reveals $\nu_e$ excess
- Excess not consistent with LSND signal
- Currently under investigation
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Low E checklist

- Data integrity checks
- Double check background calculations
- New backgrounds?
  - (i.e. not considered in original analysis)
  - N.B. If this is a background it may be relevant for other experiments searching for $\nu_\mu \rightarrow \nu_e$

- New physics?
- Looking at new/more data
Integrity checks

- Detector anomalies: none found
- Example: time distribution of $\nu_e$ events is flat
- Hand scanned all events: nothing pathological found

**event display of typical $\nu_e$**
Muon Internal Brem

- Apply recon and PID to clean muon CCQE events
- Directly measure rate of final state muon $\nu_e$ backgrounds

Data-MC excess, but note the scale!

Statistical uncertainties only!
“Dirt” Backgrounds

- before box-opening, fit yielded
  - meas/pred = 1.00±0.15
- fit in different (open) sample yields
  - meas/pred = 1.08±0.12

Results from dirt-enhanced fits

visible energy (GeV)

dist to tank wall along track (cm)
Lower energy threshold

- More data should help
- Extended threshold to lower energy
  - required extension of systematics
- Excess persists below 300 MeV
- New bin is even more dominated by mis-ID $\nu_\mu$
Lower energy threshold

- More data should help
- Extended threshold to lower energy
  - required extension of systematics
- Excess persists below 300 MeV
- New bin is even more dominated by mis-ID $\nu_\mu$

[Graph showing data points and error bars with labels for MiniBooNE data, expected background, $\nu_\mu$ background, and $\nu_e$ background. The graph highlights a new bin.]
## Background Breakdown

<table>
<thead>
<tr>
<th>reconstructed ν energy bin (MeV)</th>
<th>200-300</th>
<th>300-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>total BG</strong></td>
<td>284±25</td>
<td>274±21</td>
<td>358±35</td>
</tr>
<tr>
<td><strong>ν_e intrinsic</strong></td>
<td>26</td>
<td>67</td>
<td>229</td>
</tr>
<tr>
<td><strong>ν_μ induced</strong></td>
<td>258</td>
<td>207</td>
<td>129</td>
</tr>
<tr>
<td><strong>NC π^0</strong></td>
<td>115</td>
<td>76</td>
<td>62</td>
</tr>
<tr>
<td><strong>NC Δ→Nγ</strong></td>
<td>20</td>
<td>51</td>
<td>20</td>
</tr>
<tr>
<td><strong>Dirt</strong></td>
<td>99</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td><strong>other</strong></td>
<td>24</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td><strong>DATA</strong></td>
<td>375±19</td>
<td>369±19</td>
<td>380±19</td>
</tr>
</tbody>
</table>
Visible Energy & Angles

• Recall: two-body kinematics allow $\nu$ energy reconstruction from $E_{\text{lepton}}$ and $\theta_{\text{lepton}}$

$$E_{\nu}^{QE} = \frac{1}{2} \frac{2M_p E_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)\cos\theta_\ell}}$$

• no anomalies in these distributions
$E_\ell$ & $\theta_\ell$ in $E_\nu$ bins

Excess distributed among $E_\nu$, $\cos \theta_\nu$ bins

At higher energy, data are well-described by predicted background
New BG? Physics?

Difficulty distinguishing single photons from electrons

- Photo-nuclear absorption
  - Can produce low energy “$\nu_e$” events
- No effect on $E_\nu > 475$ MeV
- Anomaly-mediated photon production
- Both under active investigation
More data should help!

- Double check everything in MiniBooNE
- Same detector with different beam $\Rightarrow$ NuMI
- Same beam with different detector $\Rightarrow$ SciBooNE
Same Det. Diff. Beam

- MiniBooNE can see neutrinos from the NuMI beam
- Off-axis beam
  - 110 mrad
- Enriched $\nu_e$ sample
- Very different energy for $\nu_\mu$ components
- Results presented Dec 14
- New experiment at Fermilab
- Near Detector in BNB
- Better at distinguishing photons from electrons
- Check MiniBooNE’s background estimates

Spokespeople:
T. Nakaya, Kyoto University
M.O. Wascko, Imperial College
• Three subdetectors:
  • SciBar, EC, MRD

• Data run started June 2006

• Now taking data (as I speak!)
Data Progress

- Expect $2.0 \times 10^{20}$ POT total
- $1.0 \times 10^{20}$ neutrino
- $1.0 \times 10^{20}$ antineutrino
- Collected $0.54 \times 10^{20}$ POT antineutrinos already
- Now running in neutrino mode
- Only 1 dead channel in $14,336 + 256 + 362$
What’s Next?

- MiniBooNE is publishing more papers:
  - Neutrino cross section measurements
  - Joint analysis of MiniBooNE, LSND and KARMEN data
  - More exotic oscillation analyses
    - $\nu_e$ disappearance
    - 2 or 3 sterile neutrinos with CP violation
      - MiniBooNE analysis coming soon
  - Results of NuMI-MB analysis very soon
    - Fermilab “Wine & Cheese” Seminar Dec 14
- MiniBooNE is pursuing $\bar{\nu}_e$ appearance search now
Summary

- MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ 2$\nu$ oscillations
- Incompatible with LSND $\overline{\nu}_\mu \rightarrow \nu_e$ oscillation signal at 98% CL
- Low energy excess under investigation
- More data coming soon

arXiv:0704.1500 [hep-ex]